SUMMARY REPORT

Advanced EMI Sensor Demonstration at the Central Impact Area, Camp Edwards, MA

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1. Introduction

Classification using the MetalMapper and TEMTADS 2x2 advanced electromagnetic sensors was demonstrated at the Central Impact Area (CIA) of Camp Edwards on the Massachusetts Military Reservation, Cape Cod MA in 2012. This report summarizes the results of that demonstration. The document *Implementing Classification on Munitions Response Sites* (Ref. 1) provides practical information for deciding whether classification is appropriate to a particular site and how it is best implemented.

Central Impact Area, Camp Edwards, MA –wide variety of munitions used, dense vegetation, some areas flat and others heavily cratered, minimal geologic interference, very high clutter density, primary concern is potential groundwater contamination by munitions constituents

Munitions of Primary Concern– 60-mm, 81-mm, and 4.2-in mortars; 105-mm and 155-mm projectiles; priority is given to maximizing removal of munitions constituents by net explosive weight

Results – MetalMapper and TEMTADS 2x2 were used to successfully classify greater than 90% of the targets of interest and eliminate 50% to 80% of the clutter. Production contractor field crews collected high quality cued MetalMapper and TEMTADS 2x2 data. Both production contractor geophysicists and the developers of classification methods were successful in using these data to achieve substantial classification. Among the analysts, there was some variation in performance but even the poorest performer was able to correctly eliminate over 75% of the clutter while identifying 95% of the TOI.

Classification is motivated by the need to perform munitions response more cost-effectively so that limited clean up dollars can be used to reduce real risk on munitions-contaminated sites sooner. The estimated liability in the FY10 Defense Environmental Programs Report to Congress for Munitions Response is \$15.2B. (Ref. 2) The bulk of this liability is \$10.0B for the 1703 sites identified in the Formerly Used Defense Sites (FUDS) program and \$4.4B for the 2433 sites identified on Active Installations. The remaining \$0.8B is in Base Realignment and Closure (BRAC). The estimated completion dates for many sites, particularly in the FUDS program, are decades out if they are to be cleaned up at planned funding levels using current practice.

When a munitions response site is cleaned up, in most cases, it is mapped with a geophysical sensor and the locations of all detectable signals are excavated. Geophysical sensors detect metal and, therefore, many of the detections do not correspond to munitions, but rather to harmless metallic objects. Field experience indicates that 95-99% or more of objects are found to be nonhazardous. Current industry standard technology does not provide a means to discriminate between munitions and other items, termed "clutter." As a result, most of the costs to remediate a munitions-contaminated site using current methods are spent on excavating targets that pose no threat.

Classification is a process used to make a decision about the likely origin of a signal. In the case of munitions response, high-quality geophysical data can be interpreted with physics-based models to estimate parameters that are related to the physical attributes of the object that resulted in the signal, such as its physical size and aspect ratio. The values of these parameters may then be used to determine whether the signal arose from a munition or harmless clutter. With reliable classification, only the munitions need to be removed from the site.

The Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) have supported the development of purpose-built advanced electromagnetic sensors and associated analysis methods for classification. Following the successful demonstration of classification methods in controlled test environments, ESTCP initiated a Classification Pilot Program to validate the application in real-world conditions. The goal of the program is to demonstrate that classification decisions can be made using an explicit approach, based on principled analysis that is transparent and reproducible. The demonstrations are planned and conducted in cooperation with regulators and program managers in the Services.

The physics governing the electromagnetic response of a metal object is well understood and predictable. Data collected with these sensors contain the same information content on any site and demonstrations to date have confirmed that classification works predictably. Nevertheless, demonstrations will be required at a number of sites to represent the wide variability in munitions types, target densities, terrain, vegetation, geology, land use history, future land use, and other site characteristics that will affect the applicability of classification and to establish cost effectiveness and implementability. The demonstrations also present an opportunity to work out standard operating procedures and establish quality control (QC) measures. Prior demonstrations have been conducted at a number of sites across the country. Details about past and ongoing demonstrations can be found on the SERDP-ESTCP web site at http://serdp-estcp.org/Featured-Initiatives/Munitions-Response-Initiatives/Classification-Applied-to-Munitions-Response.

The demonstration at Camp Edwards continues the practice of production geophysics contractors collecting and analyzing advanced sensor data using the MetalMapper and TEMTADS 2x2. One purpose of the demonstration was to train production contractors in the analysis of data from these advanced sensors. This is an important consideration in evaluating and applying the results. We discourage potential customers from using the results of any single demonstration to rank performers and make contracting selections; analysts will gain experience and improve. Data were also analyzed by experienced teams from the developers of the classification methods. Table 1 shows the participants and their roles in the demonstration.

Table 1-1. Participants in the Classification Demonstration at the Central Impact Area

<table>
<tr><th>Task</th><th>Performer(s)</th><th>Task</th><th>Performer(s)</th></tr>
<tr><td>Site Preparation</td><td>On-site contractor</td><td rowspan="2">Data Analysis</td><td rowspan="2">CH2M HILL
Dartmouth
Parsons
SAIC
Sky Research</td></tr>
<tr><td>Modified EM61-Mk2 Data Collection and Target Selection</td><td>On-site contractor</td></tr>
<tr><td>MetalMapper Data Collection</td><td>Parsons</td><td>Intrusive Investigation</td><td>Parsons</td></tr>
<tr><td>TEMTADS 2x2 Data Collection</td><td>Nova Research
CH2M HILL</td><td>Scoring</td><td>Institute for Defense Analyses</td></tr>
</table>

2. Central Impact Area Demonstration Flow

The sequence of Phase 1 of the demonstration is outlined in the flow chart in Figure 2-1.

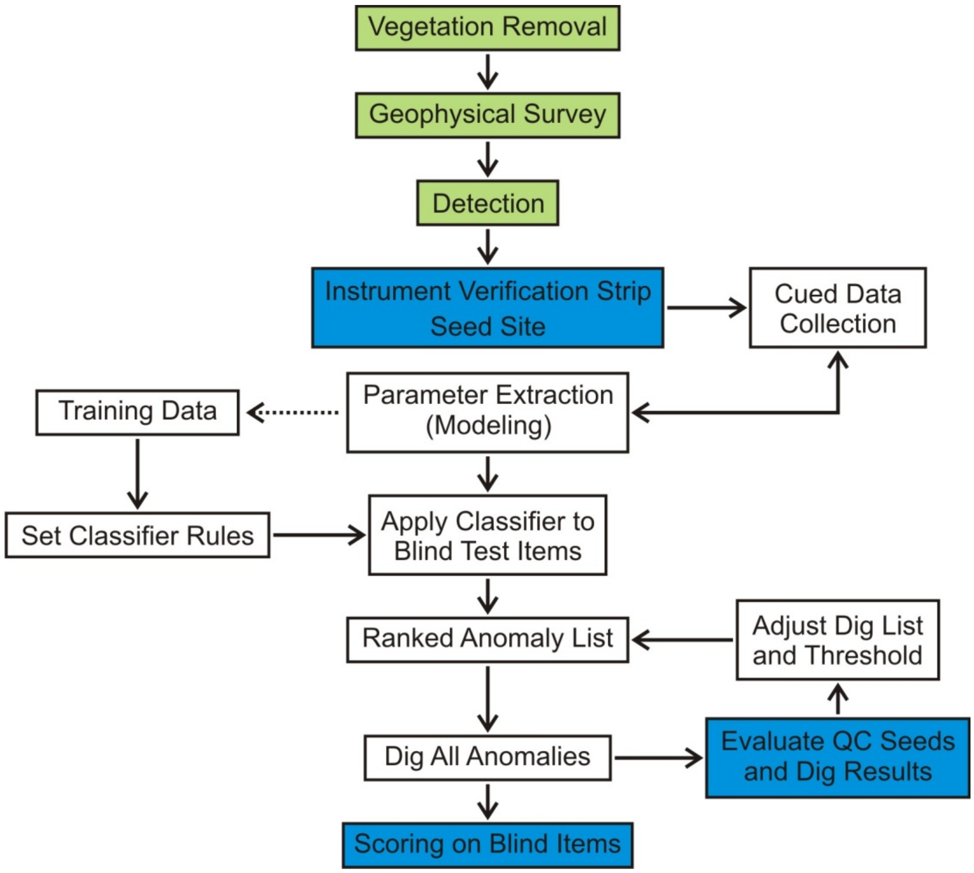

Figure 2-1. Flow chart outlining steps in the demonstration at the Central Impact Area. Green boxes are tasks performed by the on-site contractor, blue boxes are tasks performed by ESTCP. All others tasks were performed by demonstrators.

Vegetation was removed from the demonstration areas using a robotic removal system. Although use of this system was dictated by safety considerations, the resulting site conditions were less than optimal, necessitating substantial extra survey effort, Figure 2-2. Future operations can be facilitated by more attention to site preparation.

The site was surveyed with a specially-modified EM61-MK2 deployed in litter-carry mode to provide an initial list of detected anomalies. This sensor has been configured with a sampling gate much later in time than a standard EM61-MK2 in order to discriminate against small metallic clutter.

Prior to cued data collection, an instrument verification strip (IVS) was installed and the site was seeded with inert munitions and medium industry standard objects (ISOs), 2-in nominal X 8-in pipe nipples. (Ref. 3) Data collectors visited the IVS twice daily to verify equipment function at the start and end of each day. Since there are few native unexploded ordnance (UXO) on most munitions response sites, QC seeds are routinely used to ensure sufficient targets of interest (TOI) to provide adequate opportunities to demonstrate that the classification process can reliably identify the TOI. This is less of a concern at this site but the QC seeds also give us a way to compare results among sites.

Figure 2-2. Site conditions in the demonstration area after the robotic vegetation clearance

The MetalMapper or TEMTADS 2x2 were used to collect cued data over each anomaly. Since the QC seeds were emplaced after the EM61 detection survey, their locations were added to the detection list. All detected targets were dug up to provide complete ground truth for the purposes of determining performance. The UXO technicians photographed each item that was dug and recorded its location, depth, and description. As expected for a site as heavily used as the CIA, most excavations resulted in the recovery of multiple metal items.

Targets of Interest (TOI) are all objects that must be removed from the site. Typically the TOI will include all known or suspected munitions types, any other unexpected munitions, munitions parts that present an explosive hazard, and all seeded items. For this demonstration, the local site team determined that all items that could be potential groundwater contamination sources should also be TOI. This includes both intact rounds and substantial parts of rounds that could contain significant quantities of explosives. In either case, geophysical measurements cannot determine whether a round contains explosives; TOI are defined by the status of the metallic round rather than the presence of explosives.

The geophysical data were passed to the data analysis teams. A complete overview of the analysis procedures can be found in Ref 1. Briefly, the analysts used methods based on the dipole model to estimate target parameters. Analysts were offered training data from test pit measurements and the opportunity to request additional training data from the recovered targets, as though they were doing a limited number of sample digs. These data were used to set classifier rules – the decisions that separate the anomalies into TOI and non-TOI. The classifiers were then applied to all of the targets that remained blind for each demonstrator. Since training data was by request, the blind target set was different for each demonstration.

The product required from each analyst was a ranked anomaly list as shown in Figure 2-3. One and only one judgment was required for each entry on the anomaly list; in the case of multiple items, the anomaly was classified as "likely TOI" if any of the items were TOI. Following any training data, the first items on each anomaly list are those targets for which reliable parameters cannot be extracted and therefore must be dug. Next are those items which the analyst is the most confident are TOI. The items are ranked according to decreasing likelihood that the item is a TOI. Any items which the analyst was able to analyze but was not able to make a classification decision on at this

Initial Ranked Anomaly List

Anomaly ID	Dig on First Pass	Type	Comment
718	Y		Classifier training data
207	Y		
2498	Y		Unable to extract reliable parameters
247	Y	105 mm	
1114	Y	4.2 in	High likelihood TOI
69	Y	155 mm	
811	Y	81 mm	
313	N		Unable to classify
883	N		
...	N		
...	N		
...	N		High likelihood not TOI
...	N		
...	N		
...	N		
...	N		
...	N		
...	N		

First Pass Threshold

Final Ranked Anomaly List

Anomaly ID	Dig	Type
718	Y	
207	Y	
2498	Y	
247	Y	105 mm
1114	Y	4.2 in
69	Y	155 mm
811	Y	81 mm
313	Y	105 mm
883	N	
...	N	
...	N	
...	N	
...	N	
...	N	
...	N	
...	N	
...	N	
...	N	

Final Threshold

Figure 2-3. Initial and Final Ranked Anomaly Lists. A detailed description is in the text.

time were placed next on the anomaly list. Last are all those items that the analyst was confident are not TOI ranked by their likelihood. This initial list is shown in the left panel of Figure 2-3.

When analysts submitted their initial prioritized lists, the QC seeds were used to provide feedback if seed targets were missed. Analysts were also provided with the ground truth information on all anomalies in the red part of their lists and any requested anomalies in the yellow part. This is signified by the threshold on the left side of Figure 2-3. Based on this information, the analysts were then allowed to revisit their rankings and assignments for all items that were still blind until they were satisfied that the best possible classification had been achieved.

In the final list, shown in the right panel of Figure 2-3, the analyst was required to provide a threshold that corresponds to the division between those items recommended for digging and those that can safely remain in the ground. That is, the list is all red and green with a threshold separating the two categories. The final prioritized anomaly lists were scored against the emplaced blind seeds and recovered targets by IDA.

3. Site Description and Preparation

Portions of Massachusetts Military Reservation were used by the military beginning in the early 1900s. (Ref. 4) The Central Impact Area on Camp Edwards has been used as an impact area for artillery and mortars from the late 1930s until 1997. During the late 1940s, the CIA also contained Navy air-to-ground rocket ranges that utilized 2.25 inch rockets. Various types of munitions including 37 mm, 40 mm, 75 mm, 90 mm, 105 mm, and 155 mm artillery projectiles and 50 mm, 60 mm, 70 mm, 81 mm, 3-inch, and 4.2-inch mortars have been fired into the CIA. These munitions include high explosive (HE) charges designed to explode upon impact, and practice or "inert" rounds which do not contain an HE charge but may contain a spotting charge designed to emit smoke upon impact.

The predominant HE charge used in pre-WWII munitions contained TNT. Post-WWII artillery and mortar munitions used Composition B for the HE charge, which is a mixture of RDX and TNT. The Low-Intensity Training Round (LITR) is an artillery practice projectile that was introduced in 1982 to reduce the noise associated with HE explosions, since this noise was a source of complaints from the public abutters. The LITR includes a spotting charge containing perchlorate. The use of HE artillery projectiles was discontinued in 1989, and the firing of all munitions into the CIA was discontinued in 1997.

HE munitions that did not explode (UXO) or that partially functioned (UXO low order) have accumulated within the CIA during its use. UXO located along roadways or at other locations that presented a safety hazard due to human access have historically been blown in place using an explosive donor charge. Blow-in-place (BIP) operations were also used to clear areas for site investigation under the Impact Area Groundwater Study Program (IAGWSP) starting in 1997. Post-BIP soil sampling and removal of soil contaminated by BIP activities have been conducted since 1999 under the IAGWSP.

The demonstration was conducted on six acres in the Central Impact area as shown in Figure 3-1. A three-acre area (twelve grids) in the flatter, southern portion of the site, along what is known as Tank Alley, was designated for survey using the vehicle-borne MetalMapper. Twelve grids in the more cratered northern part of the site were assigned to the portable TEMTADS 2x2. At the request of the site team, the TEMTADS 2x2 also collected data over 300 anomalies in the southern grids to provide a performance comparison.

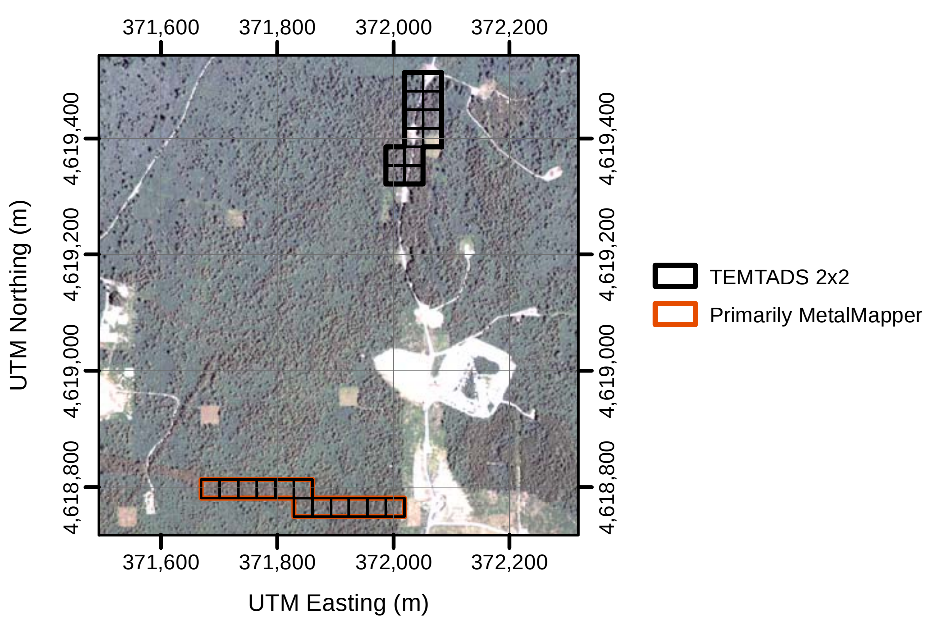

Figure 3-1. Location of the demonstration grids in the Central Impact Area

The objective of the ESTCP demonstration was to detect and correctly classify TOI on the site with emphasis on removing potential groundwater contamination sources; current practice (Ref. 4) has removed an estimated 75 to 85% of the munitions. The analysts were provided information about the historical use and known munitions types. But, the direction specified that, in addition to these munitions, any unexpected munitions would also be considered TOI.

At most live sites, the number of targets of interest is small, far from enough to provide adequate opportunities to demonstrate that classification can reliably identify the TOI. Although this is not likely to be a problem at this site, the demonstration area was seeded with inert TOI to serve as process QC checks. The seeds are listed in Table 3-1. The seeds included not only inert munitions, but also industry standard objects. (Ref. 3) The ISOs are also considered TOI and expected to be both detected and correctly classified.

Table 3-1. Seeds Emplaced for the Central Impact Area demonstration

Item	Number	Depth range (cm)*
Industry Standard Object - Medium	20	15-45
81-mm mortar	40	15-45
105-mm projectile	40	25-75
4.2-in mortar	20	30-60
155-mm projectile	40	25-75

*Depths are to the center of the object.

No attempt was made to separate the emplaced seeds from the surrounding clutter. For safety, seeds were emplaced using standard anomaly avoidance procedures. For realism, the emplacement teams were instructed to replace any metal dug up during emplacement with the seeded object.

4. EM61 Detection Survey

The anomaly selection criterion was based on previous work at this site and was designed to detect 60-mm mortars; consistent with the overall site objective of removing as many potential groundwater contamination sources as possible. All anomalies with an amplitude greater than 27 mV in channel 2 of the EM61 were automatically selected. This is a very cluttered site; the threshold chosen is very close to the noise floor, Figure 4-1. Lowering the threshold further would result in an unacceptable number of anomalies, many of which would be noise peaks.

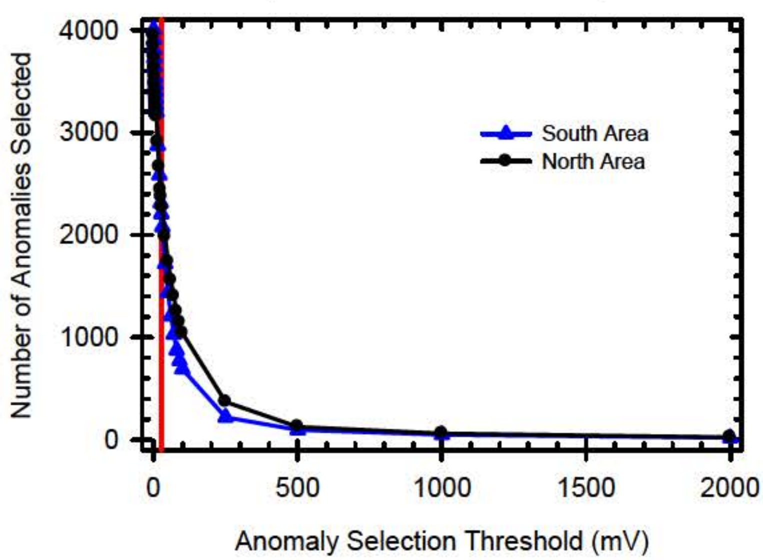

Figure 4-1. Number of anomalies selected as a function of selection threshold for the north and south grids. The threshold used in this demonstration (27 mV) is indicated by the red line.

A total of 4722 anomalies were identified on the demonstration grids; 2435 in the northern grids and 2287 in the southern grids, Figure 4-2. By itself, the anomaly density of nearly 800 anomalies per acre is very high. The anomaly selection criteria are weighted toward larger items that pose the most risk of groundwater contamination; they do not guarantee that smaller munitions such as 37-mm projectiles will be found. This is the highest anomaly density in which these methods have been attempted.

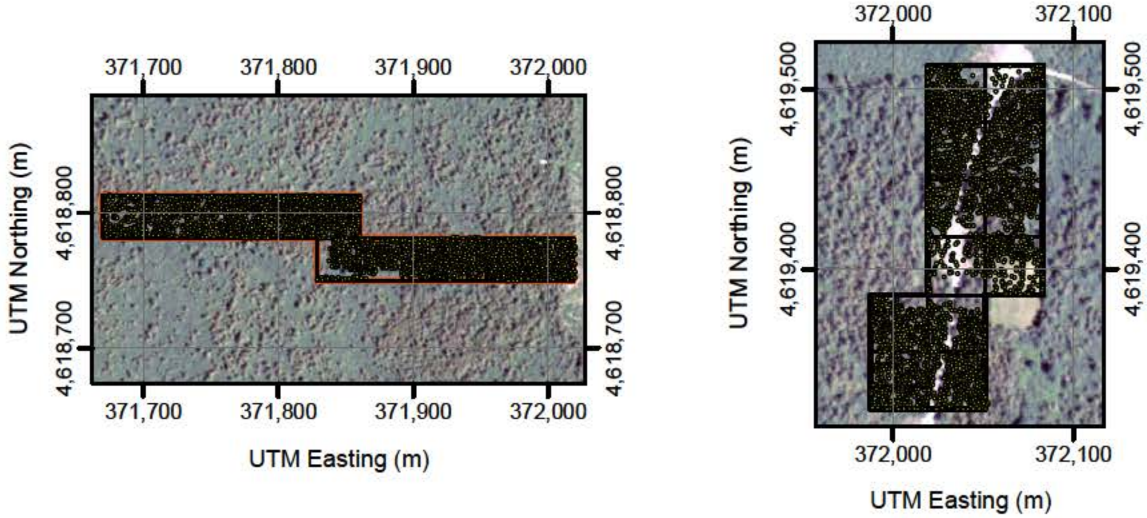

Figure 4-2. Anomalies identified in the southern area (left panel) and northern area (right panel)

After the demonstration was complete, the on-site contractor re-analyzed the EM61 survey data from on grid (42_53). Using their analysis methods, this analyst selected 70 additional anomalies (out of 228 total). Of these, 13 met their dig criteria and six were found to be TOI. The results reported here only apply to the anomalies identified by the ESTCP project involved in this demonstration.

5. MetalMapper Cued Data Collection

The MetalMapper developed by Geometrics is designed to be a stand-alone survey and cued detection system. The system, shown in Figure 5-1, is composed of three orthogonal 1-m x 1-m transmitters for target illumination and 7 three-axis receivers for recording the response. Its sampling is electronically programmable and therefore flexible. It measured the decay curve up to 8 ms after the transmitters were turned off. It was deployed in a sled configuration mounted to a tractor. Centimeter-level GPS is used for navigation and geolocation and an inertial measurement unit (IMU) is used to measure platform orientation. In cued mode, MetalMapper is positioned over each anomaly on its target list and collects the full suite of data while stationary. The digital data set produced by MetalMapper is fully described in Ref. 5.

Figure 5-1. Schematic and photo of the MetalMapper as used on the CIA

In this demonstration MetalMapper was used only in cued mode. Parsons collected MetalMapper data over 2273 of the 2287 anomalies in the southern grids; fourteen of the anomalies were blocked by vegetation. Of course, no classification is possible on the anomalies for which data was not collected; they are placed at the top of the dig list. These results are documented in Ref. 6.

The most common QC failure was that the MetalMapper was positioned too far from the anomaly to obtain reliable parameter estimates. If the separation between the center of the MetalMapper and the anomaly location was more than 40 cm, the anomaly was revisited the next day and additional data collected within the 40-cm specification.

This data collection team averaged 227 cued anomalies per day (32 per hour). They required 30 QC recollects, corresponding to a little over 1% of the anomalies measured.

6. TEMTADS 2x2 Cued Data Collection

The TEMTADS 2x2 array is comprised of four individual EMI transmitters with 3-axis receivers, arranged in a 2 x 2 array as shown in Figure 6-1. The center-to-center distance is 40 cm, yielding an 80 cm x 80 cm array. The data acquisition computer is mounted on a backpack worn by one of the data acquisition operators. The second operator controls the data collection using a personal data assistant (PDA) which wirelessly communicates with the data acquisition computer. The second operator also manages field notes and team orienteering functions.

Figure 6-1. Schematic and photo of the TEMTADS 2x2 array

For each series of measurements with the array, the four transmitters are energized sequentially. After each excitation pulse, the response of all twelve receive coils is recorded, resulting in 48 (4 x 4 x 3) transmit/receive pairs. Data were recorded for 25 ms after transmitter turn-off. (Ref. 7)

The TEMTADS demonstrators were contracted for a smaller survey than the MetalMapper crew. Due to the site conditions, the TEMTADS team was unable to follow their normal procedures. They removed the handle from the back of their sensor array (Figure 6-1) and carried it with two field technicians (Figure 2-2). This did not impact the number of anomalies visited each day but did require extra personnel in the field. They were able to collect cued data on 1013 anomalies in the northern grids and 300 in the southern grids, Figure 6-2. Productivity with the TEMTADS 2x2 averaged 250 anomalies per day with only 9 re-collects (less than 1%) required.

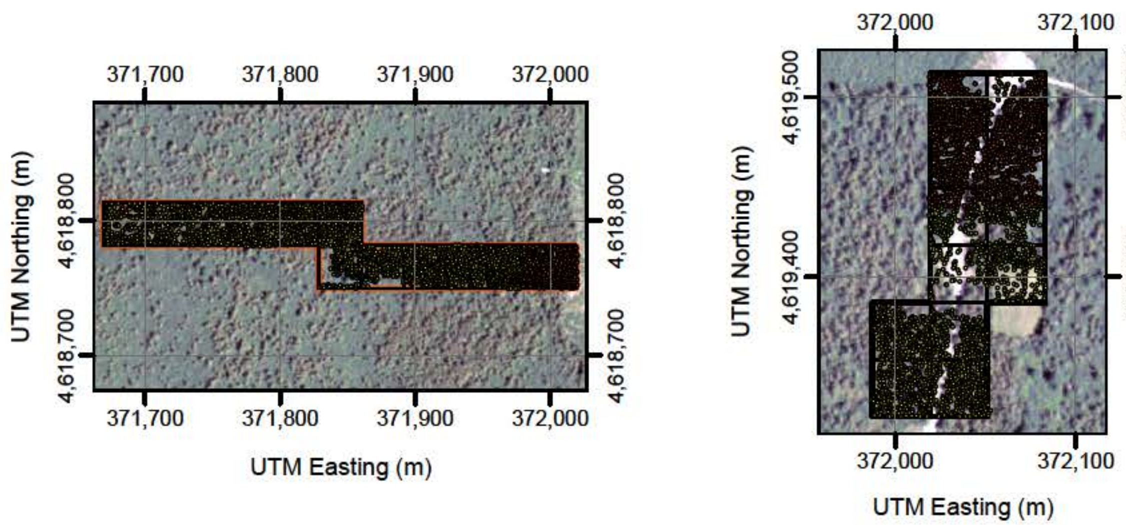

Figure 6-2. Anomalies identified in the southern (left panel) and northern (right panel) grids of the demonstration with the TEMTADS cued data indicated by red dots

7. Intrusive Investigation

The nearly 5,000 anomalies identified in the 24 grids chosen for the demonstration are roughly twice as many as the resources available for intrusive investigation. The site stakeholders agreed that the demonstration should be split into two phases; in Phase 1 roughly half of the cued targets would be classified, intrusively investigated, and scored (Figure 7-1). The Phase 1 results are presented in this report. The plan for Phase 2 will be decided by the stakeholders following acceptance of this report.

A total of 1336 anomalies were investigated in Phase 1, 905 in the southern grids including all 300 of the anomalies surveyed by both systems and 431 in the northern grids. A summary of the recovered items is given in Table 7-1. An average of three items was recovered from each anomaly investigated; each item recovered is counted individually in Table 7-1.

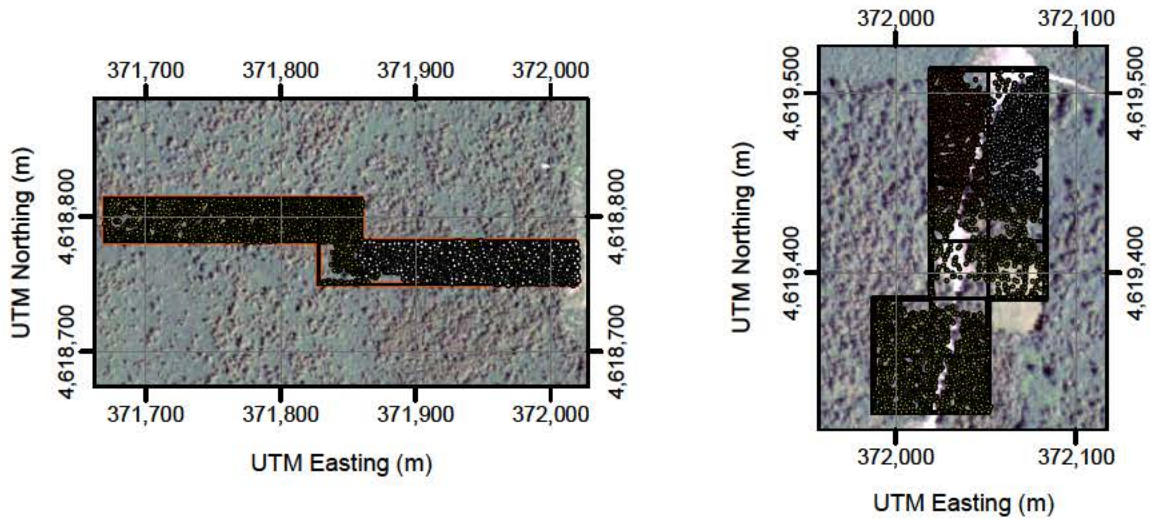

Figure 7-1. Anomalies intrusively investigated in Phase 1 of the demonstration (white symbols)

Table 7-1. Intrusive Results from Phase 1 of the CIA Demonstration

Recovered Item	Southern Grids	Northern Grids
UXO	7	1
Other TOI	103 (27 seeds)	26 (6 seeds)
Munitions Debris	2647	1129
Other Debris	13	72
No Contact	3	0
Total	**2773 (905 anomalies)**	**1227 (431 anomalies)**

There are several things to note from the intrusive results. As at most heavily used sites, the overwhelming majority of metal recovered was munitions-related debris. Contrary to many sites, most of the TOI recovered in Phase 1 was native TOI with only about 25% corresponding to the QC seeds. Finally, as stated above, there were approximately 3 metal items recovered from each anomaly. This ratio, coupled with the high anomaly density, made this a good test for classification.

8. Classification Results

Both data sets were analyzed by multiple demonstrators including the firms that collected the data and the developers of the analysis methods. The results of classification on the data from MetalMapper and TEMTADS 2x2 will be presented individually followed by a brief comparison of the results on the 300 overlap targets shown in the left panel of Figure 6-2.

8.1 Analysis of MetalMapper Data

The MetalMapper data were analyzed by five analysts including both the developers of the analysis methods and production geophysicists. An overview of their results is shown in Figure 8-1.

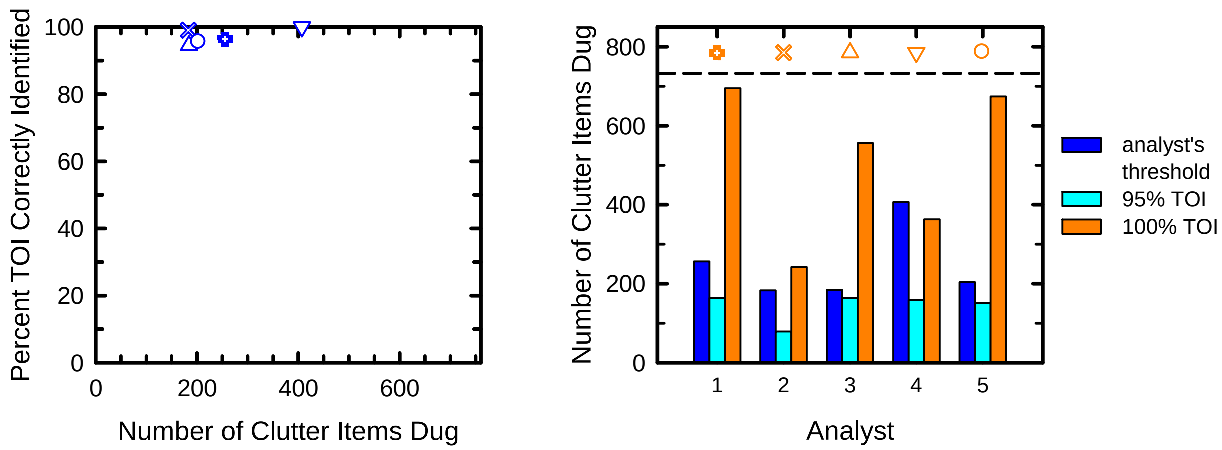

Figure 8-1. Summary of the performance of the five analysts working with the MetalMapper data at the CIA. The left panel plots the percent TOI correctly classified versus the number of clutter at each analyst's specified stop dig point. The right panel shows the number of clutter items (out of 732 total - denoted by the horizontal dashed line) required to be dug at the analyst's threshold, to correctly classify 95% of the TOI, and to correctly classify 100% of the TOI.

The panel on the left of Figure 8-1 shows the percent of TOI correctly classified versus the number of clutter at each analyst's specified operating threshold. Desired performance is to correctly classify 100% of the TOI and eliminate all the clutter. The right panel shows the number of clutter items (out of 732 total) required to be dug at each analyst's threshold, to achieve 95% correct classification of TOI and to achieve 100% correct classification of TOI.

Overall, the results achieved by the analysts working with MetalMapper data are very good. If the site objectives can be met by correctly classifying 95% of the TOI, which is higher than the estimates of performance of past work at this site, most analysts can eliminate 75% of the clutter. The analysts' thresholds generally reflected this; at their specified thresholds, all analysts correctly classifying 95% or more of the TOI and four out of five eliminated more than half of the clutter. If 100% correct classification of TOI is required, including the smallest TOI, then most analysts would have to dig substantially more of the anomalies.

The values plotted in Figure 8-1 are derived from the individual analyst's receiver operating characteristic (ROC) curves. Several examples are presented in the following paragraphs.

Geophysicists from Sky Research analyzed the MetalMapper data collected using methods developed at Sky. (Ref. 8) The results of this analysis are shown in Figure 8-2. The colors on the plot correspond to the red and green colors in the final ranked anomaly list as shown in Figure 2-3.

The red are the items the analyst classified as "high likelihood TOI" and the green are those the analyst called "high likelihood not TOI." The graph plots the percent of the targets of interest correctly classified on the vertical axis and the number of clutter items on the horizontal axis. The offset from zero in the starting point reflects any training data that the analyst requested. Anomalies classified as "can't extract reliable parameters" are represented by the short initial black line. The blue dot represents the threshold selected by the analyst, the cyan dot shows the point on the ranked anomaly list where 95% of the targets of interest are captured, and the orange dot shows the point where 100% of the target of interest are captured. Ideally, a classifier would correctly identify all targets of interest in the red with zero clutter and all of the clutter would be in the green. In this case, the red part of the curve would go straight up to 100% and the green part of the curve would

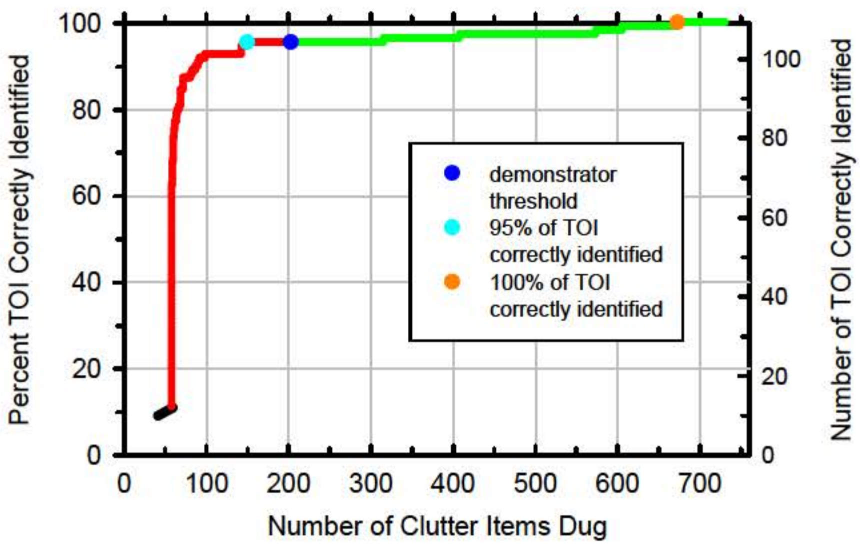

Figure 8-2. Results of the Sky Research analysis of the MetalMapper data

run straight across the top axis. Success in these demonstrations was defined by eliminating the maximum amount of clutter while correctly identifying a sufficient fraction of the TOI.

In this phase of the MetalMapper analysis, there were 732 total clutter items determined from the ground truth. This analyst was able to correctly classify 528 of these items at their threshold for a savings of over 70% of the clutter digs. Working down the anomaly list from Sky, 95% of the TOI were correctly classified after 151 clutter items were dug.

Several groups analyzed the MetalMapper data using the UX-Analyze module of Oasis montaj. Figure 8-3 shows the results of the analysis by Parsons, the group that collected the data. (Ref. 6) This analyst correctly classified 548 of the clutter items at his threshold while identifying 95% of the TOI.

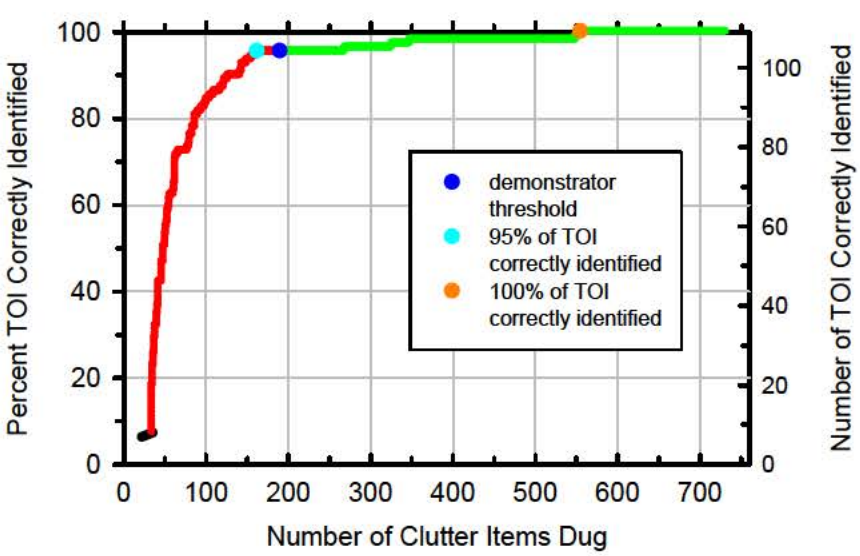

Figure 8-3. Results of the Parsons analysis of the MetalMapper data

The final example presented is an analysis performed by scientists from Dartmouth College using methods developed at Dartmouth. Their results are shown in Figure 8-4. These analysts correctly identified 99% of the TOI at their threshold while avoiding over 70% of the clutter digs. At the point on their ranked anomaly list where 95% of the TOI had been captured, only 79 (11%) of the clutter items had been dug.

All of the analysts were able to identify 95% of the TOI while digging between 11% and 22% of the clutter. Identifying the remaining 5% of the TOI was much more challenging in most cases, requiring as much as 95% of the clutter to be dug in one case. The items that were difficult to correctly classify will be discussed in Section 8. Reference to Figure 8-1 shows, however, that four of the five analysts' specified stop dig threshold resulted in clutter digs (blue bar) close to the best case 95% correct classification of TOI point (cyan bar) and would serve as an acceptable working point.

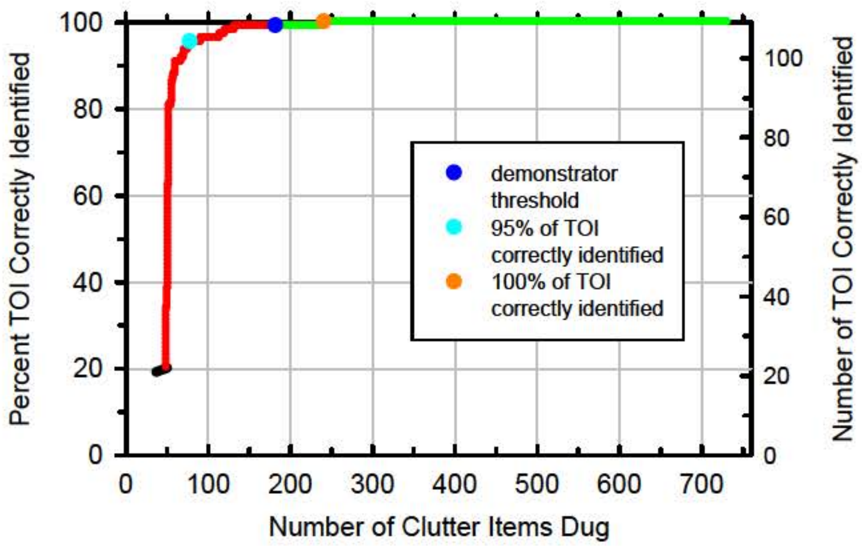

Figure 8-4. Results of the Dartmouth analysis of the MetalMapper data

8.2 Analysis of the TEMTADS 2x2 Data

An overview of the analysis results for the four analyses of the TEMTADS 2x2 data are shown in Figure 8-5. Overall, the results achieved by the analysts working with TEMTADS 2x2 data are comparable with the results presented previously for the MetalMapper analyses. If the site objectives can be met by correctly classifying 95% of the TOI, all analysts can eliminate over half of the clutter. The analysts' thresholds generally reflected this. If 100% correct classification of TOI is required, including the smallest TOI, then most analysts would have to dig substantially more of the anomalies.

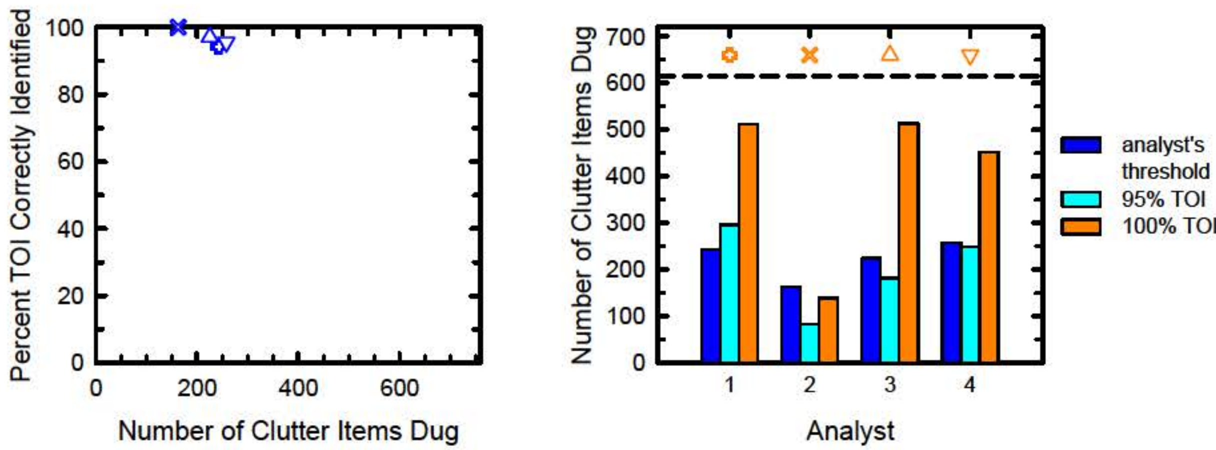

Figure 8-5. Summary of the performace of the five analysts working with the TEMTADS 2x2 data. The left panel plots the percent TOI correctly classified versus the number of clutter at each analyst's specified stop dig point. The right panel shows the number of clutter items (out of 615 total – denoted by the horizontal dashed line) required to be dug at the analyst's threshold, to correctly classify 95% of the TOI, and to correctly classify 100% of the TOI.

Geophysicists from Sky Research also analyzed the TEMTADS 2x2 data using methods developed at Sky. (Ref. 8) The results of this analysis are shown in Figure 8-6. In this phase of the TEMTADS 2x2 analysis, there were 615 total clutter items determined from the ground truth. This analyst was able to correctly classify 357 of these items at their threshold for a savings of over 55% of the clutter digs. Working down the anomaly list from Sky, 95% of the TOI were correctly classified after 249 clutter items were dug.

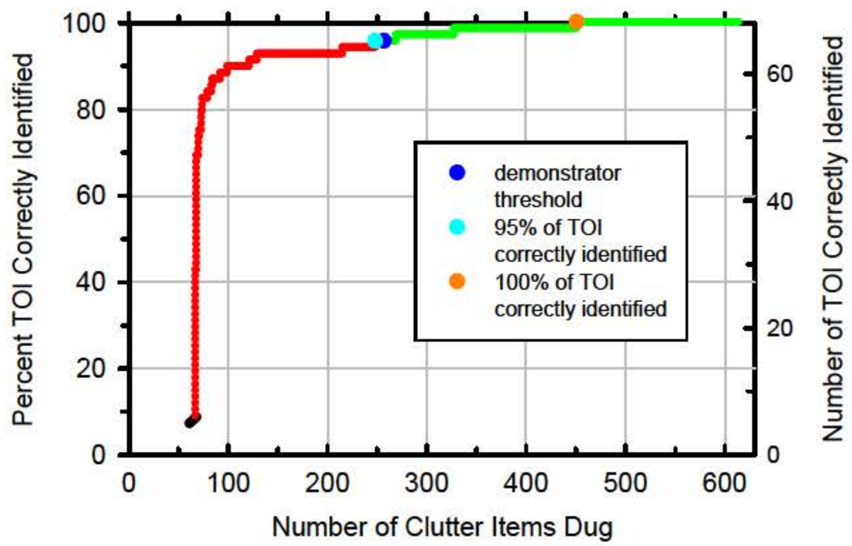

Figure 8-6. Results of the Sky Research analysis of the TEMTADS 2x2 data

The results obtained by scientists from Dartmouth College using methods developed at Dartmouth are shown in Figure 8-7. These analysts correctly identified 100% of the TOI at their threshold while avoiding over 75% of the clutter digs. At the point on their ranked anomaly list where 95% of the TOI had been captured, only 82 (13%) of the clutter items had been dug.

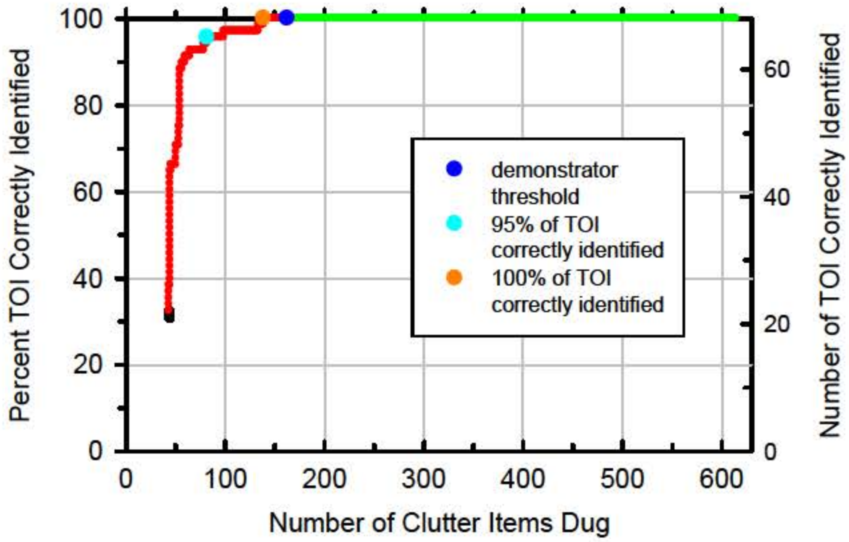

Figure 8-7. Results of the Dartmouth analysis of the TEMTADS 2x2 data

8.3 Comparison of the Two Sensors

Cued data were collected by both MetalMapper and TEMTADS 2x2 over 300 anomalies in the southern grids. A comparison of the classification performance achieved by the Dartmouth analysis team using these two data sets is shown in Figure 8-8. As can be seen, the results using the two sensors are virtually indistinguishable over this subset of the anomalies which is consistent with our expectations and results at other sites. This leads to the conclusion that either sensor can be used effectively at this site.

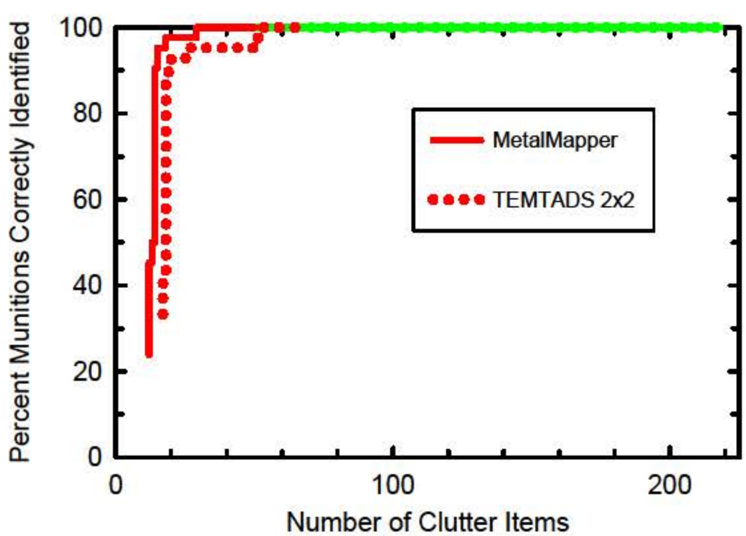

Figure 8-8. Results of the Dartmouth analysis of MetalMapper and TEMTADS 2x2 data from the overlap anomalies

9. Difficult to Classify Items

Table 9-1 lists the TOI from the MetalMapper data incorrectly classified at each analyst's specified stop dig threshold.

Table 9-1. Incorrectly classified TOI at each MetalMapper Analyst's Threshold

Analyst	1	2	3	4	5
Incorrectly Classified TOI	**1381: 60mm** 1798: 105mm Sabot **2128: cartridge** **2281: 155mm**	1329: 81mm	**1381 – 60mm** 2089: flare **2128: cartridge** **2141: 155mm** **2167: 37mm**		**1381 – 60mm** **2141: 155mm** **2167: 37mm** **2128: cartridge** **2281: 155mm**

While there is not perfect overlap, there are a number of anomalies common to several of the analysts denoted by bold labels in the table. Three of the commonly-missed items are shown in Figure 9-1. It is possible that none of these three should have been labeled TOI at this site. While they do present an explosive hazard and so would be TOI at most sites, they are at worst a minor potential source of groundwater contamination. The 37-mm projectile, CE-2167, merits additional discussion. The anomaly selection criterion used at the site and the rough site conditions make it likely that not all 37 mm's on the site were detected so no assumptions should be made about the removal of 37-mm projectiles.

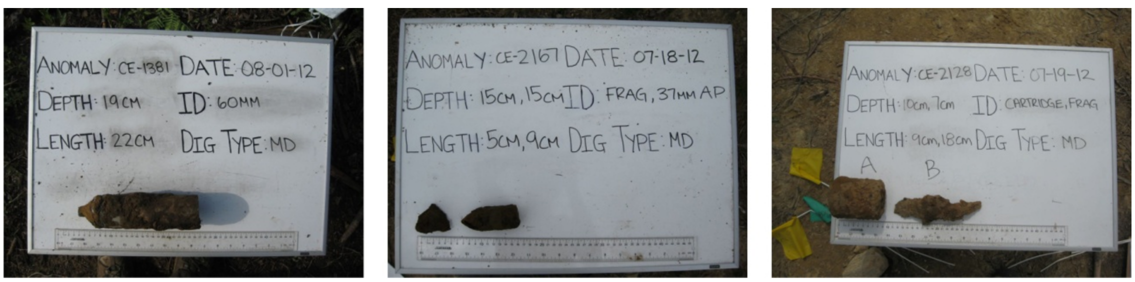

Figure 9-1. Three of the commonly-misclassified TOI in the MetalMapper data set

Two more worrisome items that were misclassified are shown in Figure 9-2. At most sites, one would expect that all 155-mm projectiles, even those at 80 and 100 cm, would be correctly classified. The very dense clutter at this site obviously prevented some of the analysts from identifying these anomalies as TOI.

Figure 9-2. 155-mm projectiles that were misclassified by some analysts

On a more positive note, a number of partial projectiles were detected and successfully classified by all analysts. Two examples are shown in Figure 9-3. At many sites these items would not be considered TOI since they present little explosives hazard. They could, however, have been filled with munitions constituents so must be considered TOI at this site.

Figure 9-3. Examples of the partial shells successfully classified at TOI in this demonstration

10. Cost Comparison

The demonstration took place on a small part of the CIA and incurred costs for many items specific to a demonstration that would not be needed in an application of classification to a real site. Nevertheless, we can extract meaningful projected performance for the technology and apply reasonable industry unit costs for various elements to arrive at a total cost comparison for clearing an example 30-acre site with and without the use of classification.

We make the following assumptions:

- The example takes place in an area with similar munitions types and the same density of anomalies as seen in the demonstration. There were approximately 800 anomalies per acre in the demonstration area; we would expect about 24,000 anomalies in a similar 30-acre area.
- One hundred four TOI (of which 8 were UXO) were found in the approximately 1.8 acres dug in Phase 1. The TOI density in the 30-zcre area is known to vary but for cost comparison purposes we will assume the density is the same throughout meaning 1,750 TOI will be found in the 30-acrea area, leaving 22,250 clutter items.
- The baseline is an EM61 survey with 0.5-m line spacing. This would be used to select anomalies for digging without classification and the same anomalies would be interrogated with MetalMapper or TEMTADS 2x2 and classified.
- The site is seeded at a rate so on average one seed will be encountered each day of MetalMapper or TEMTADS data collection. With an estimate of 24,000 total anomalies and a production rate of 200 anomalies per day, we seed a conservative 125 inert items. These QC seeds would be used whether classification was used on the site or not.
- The classification performance is as achieved by the many of the analysts with 75% of the clutter correctly identified and remaining undug.
- The unit costs are as shown in Table 10-1.

Table 10-1. Unit cost assumptions

Item	Units	Cost
Robotic Vegetation Clearance	Per Acre	$8,000
Manual UXO Surface Clearance	Per Acre	$14,000
Seed Emplacement	125 seeds	$22,650
EM61 Survey Data Collection and Analysis	Per acre	$9,000
MetalMapper and TEMTADS 2x2 Classification	Per anomaly	$25 and $35
Digs (no follow-on activities included)	Per hole	$400

With these assumptions the costs were calculated using the elements shown in Table 10-2. If classification can be done for $35 per anomaly including both data collection and analysis, which is consistent with the projections of the production companies based on prior demonstrations, a 55% overall savings is possible. Additional savings result if this cost can be lowered to $25.

Table 10-2. Cost Comparison for 30 acres comparable to the CIA

Item	No Classification		Classification		
	Quantity	**Cost/$**	**Quantity**	**Cost/$ ($35 per anomaly)**	**Cost/$ ($25 per anomaly)**
Seeds	125 items	22,650	125 items	22,650	22,650
Survey Preparation	30 acres	660,000	30 acres	660,000	660,000
EM61 Survey	30 acres	270,000	30 acres	270,000	270,000
Anomalies Classified	n/a	0	24,000	840,000	600,000
Seeds Dug	125	50,000	125	50,000	50,000
Native TOI Dug	1,750	700,000	1,750	700,000	700,000
Clutter Dug	22,250	8,900,000	5,560	2,224,000	2,224,000
TOTAL		10,602,650		4,766,650	4,526,650
Percent Savings				**55%**	**57%**

11. Conclusions

Classification based on cued MetalMapper and TEMTADS 2x2 data was used in Phase 1 of the ESTCP demonstration at the Central Impact Area of MMR to successfully identify 95% or more of the TOI and eliminate up to 75% of the clutter. Many analysts required significantly more clutter digs to achieve 100% correct classification of TOI. Since the remediation objectives at this site are not driven by explosives safety but by potential groundwater contamination, it would appear that the most efficient remediation can be achieved by establishing 95% identification of TOI as the remedial objective. Most analysts were able to obtain this level of TOI identification at their specified stop dig points.

A comparison of the results from the 300 anomalies surveyed by both sensors shows that they perform equally well at this site. The choice of which sensor to deploy on any grid can therefore be driven by which system can most efficiently survey the terrain.

A number of the analysts have completed their analysis of the Phase 2 anomalies using the parameters and thresholds developed during Phase 1 of the project. These results are listed in Table 11-1. Resources remain for approximately 1,200 digs.

Table 11-1. Analysis results for the anomalies in Phase 2 of the demonstration

Analyst	MM-1	MM-2	MM 3	MM 4	MM-5	2x2-1	2x2-2
Must Dig	505	227	276	689	360	227	85
Safe to Leave	887	1,165	1,116	703	1,032	362	504

12. Acronyms

BIP	Blow In Place
BRAC	Base Realignment and Closure
CIA	Central Impact Area
ESTCP	Environmental Security Technology Certification Program
FUDS	Formerly Used Defense Site
GPS	Global Positioning System
HE	High Explosive
IAGWSP	Impact Area Groundwater Study Program
IDA	Institute for Defense Analyses
IMU	Inertial Measurement Unit
ISO	Industry Standard Object
IVS	Instrument Verification Strip
LITR	Low-Intensity Training Round
MMR	Massachusetts Military Reservation
QC	Quality Control
RMS	Root Mean Square
SERDP	Strategic Environmental Research and Development Program
TEMTADS	Time-domain Electro-Magnetic Multi-sensor Towed Array Detection System
TNT	Trinitrotoluene
TOI	Target of Interest
UXO	Unexploded Ordnance

13. References

1. Implementing Classification on Munitions Response Sites, ESTCP, Dec. 2011, http://serdp-estcp.org/content/download/12780/151578/version/1/file/Implementing_Classification_on_Munitions_Response_Sites_FR.pdf.

2. Defense Environmental Programs Annual Report to Congress – Fiscal Year 2010, http://www.denix.osd.mil/arc/ARCFY2010.cfm.

3. "Geophysical System Verification: A Physics-Based Alternative to Geophysical Proveouts for Munitions Response," ESTCP, July 2009, http://serdp-estcp.org/content/download/7426/94837/version/1/file/GeoSysVerif-July-09-FINAL.pdf.

4. "Impact Area Groundwater Study Program, Final Central Impact Area Source Investigation Summary Report, Massachusetts Military Reservation, Cape Cod, Massachusetts," Tetra Tech EC, Inc. July 2011.

5. MetalMapper: A Multi-Sensor TEM System for UXO Detection and Classification, ESTCP Project 200603 Final Report, February 2011, http://serdp-estcp.org/content/download/9593/122667/file/MR-200603-FR.pdf.

6. Parsons MetalMapper Data Report.

7. "Demonstration Data Report, Central Impact Area, TEMTADS MP 2x2 Cart Survey," September 2012, http://serdp-estcp.org/content/download/15823/181208/file/MR-201165.

8. Sky Analysis Report

Addendum to:

Advanced EMI Sensor Demonstration at the Central Impact Area, Camp Edwards, MA

February 2015

A1. Introduction

Subsequent to the events reported in the April 2013 report on the demonstration at the Central Impact Area (CIA) of Camp Edwards on the Massachusetts Military Reservation, Cape Cod MA in 2012 [1] additional work was performed by the two of the original demonstrators. This addendum describes the results of that work.

A2. Phase II Intrusive Investigation

Phase II of the intrusive investigation took place between May 20, 2013, and June 20, 2013, and included 1,049 of the remaining 1,386 MetalMapper-only targets not investigated during Phase I. [2] The final 337 targets were not excavated due to time constraints at the site. Table 2-1 summarizes the targets investigated and sources recovered by intrusive phase.

Table 2-1. Intrusive Results from Both Phases of the CIA Demonstration

Phase	Southern Grids Anomalies	Southern Grids Recovered Items	Northern Grids Anomalies	Northern Grids Recovered Items
Phase I	905	2773	431	1227
Phase II	1049	5109		
Total	**1954**	**7882**	**431**	**1227**

On average, 53 digs were completed per day, based on 20 intrusive days. There were some location issues during the Phase I intrusive investigation due to the proximity of sources to each other and the large number of items pulled from each hole, so more care was taken to reduce the number of holes open at one time during Phase II. This was likely the cause of the discrepancy between the dig rates for the two phases. The results of the Phase II intrusive investigation are summarized in Table 2-2.

Table 2-2. Identification of Recovered Items from Phase II

Dig Type	Number
Targets of interest (munitions and explosives of concern, material potentially presenting an explosive hazard, seed, intact round identified as munitions debris)	115
Munitions debris	4,977
Other debris	16
No contact	1
Total	**5109**

The identities of the items recovered in Phase II are in line with the Phase I results. Slightly fewer TOI were recovered in this phase but the number is within the variability expected across the site.

A3. Additional TEMTADS 2x2 Cued Data Collection

The 2013 TEMTADS data collection completed the effort begun in 2012. NRL and NAVEA Geophysics conducted a cued classification survey on the remaining 1.75 acres of the 3-acre man-portable subarea selected from within the 330-acre CIA demonstration site during the weeks of July

14 and 21, 2013. [3] The 2012 NRL survey investigated 1,005 anomalies in the northern 1.25 acres of the man-portable area. Cued data collection was conducted for the remaining 1,429 anomalies previously identified from an EM61-MK2 cart survey conducted in 2012 by National Guard Bureau contractor TetraTech. This survey used the MP System in a litter-carry configuration (Figure 3-1).

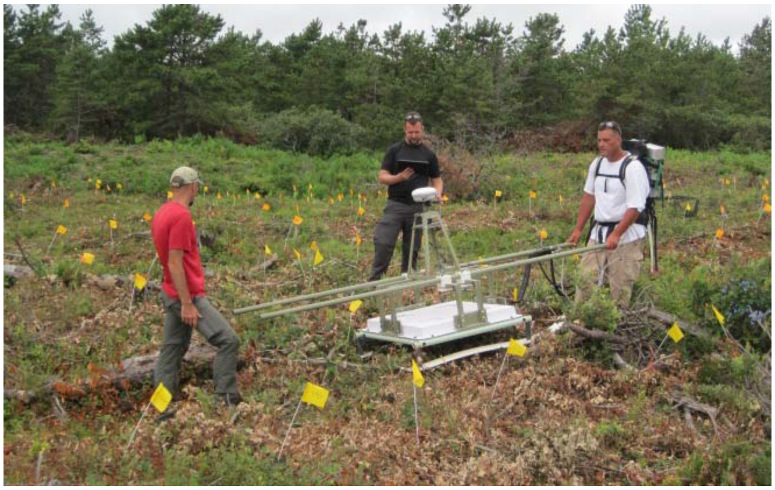

Figure 3-1 - TEMTADS 2x2 sensor in litter-carry mode configuration at MMR in 2013

Not all of the 1,429 anomalies were accessible for collection. The breakdown of data collection results is detailed in Table 3-1.

Table 3-1. Data Collection Results for the 2013 TEMTADS Deployment

Data Collection Result	Number
Collected Successfully	1291
In the Road	11
Within Test Plot/Berm Area	102
Under Brush/Tree Pile	23
Monitoring Well	1
Not Collected	1
Total	**1491**

Analysts from NAEVA Geophysics (not one of the analysts from Phase 1 of the demonstration) assisted by SAIC (one of the original analysts) processed the data from the 1,291 successful collections and used UX-Analyze to classify the anomalies as being due to targets of interest or not. The classification results are broken out in Table 3-2. The results from the 2013 anomalies mirror those in the original demonstration. A small number of the data chips were classified as "can't extract reliable parameters." These locations, of course, must be intrusively investigated. Approximately one quarter of the anomalies were classified as "likely TOI" or "unable to make a decision." These locations also require intrusive investigation. Seventy-two percent of the anomalies (930) were classified as likely clutter and can be left in the ground.

Table 3-2. Anomaly Classification for 2013 Measurements

Classification	Number
Can't Extract Reliable Parameters	11
Likely TOI	173
Unable to Make a Decision	177
Likely Clutter	930
Total	**1291**

A4. Summary

Following the initial ESTCP demonstration report summarizing the classification demonstration at the Central Impact Area, two of the original demonstrators returned to the site to perform additional work. Parsons, Inc. excavated 1049 additional anomalies referred to in the original report as the Phase II anomalies. NRL and NAEVA Geophysics collected TEMTADS 2x2 data over 1291 additional anomalies in the man-portable subarea discussed in the original report. Survey data and a ranked anomaly list resulting from deployment are available from the ESTCP Program Office.

A5. References

1. "Classification Demonstration at Massachusetts Military Reservation," https://www.serdp-estcp.org/content/download/28852/283100/version/6/file/Summary+Report+-+Former+Camp+Edwards+-+with+Addendum.pdf
2. "ESTCP Live Site Demonstrations: Massachusetts Military Reservations, Camp Edwards, MA," https://serdp-estcp.org/content/download/28043/277343/file/MR-201365-TR.pdf
3. "Live Site Demonstrations - Massachusetts Military Reservation," https://serdp-estcp.org/content/download/31801/311131/file/MR-201104-TR.pdf